STRESSES AND DEFLECTIONS IN CONCRETE PAVEMENTS CONTINUOUSLY REINFORCED WITH WELDED WIRE FABRIC

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SYNOPSIS

Laboratory experiments on simulated continuously reinforced concrete slabs are summarized, with experimental results pertaining to slab deflections, crack widths and stresses in welded wire fabric reinforcement receiving most emphasis. Some of the significant findings of these laboratory experiments are compared with field observations reported in the literature and several criteria are suggested for optimum structural design of continuously reinforced pavements.

Some of the more important conclusions reached as a result of this research, subject to the limitations imposed by the range of variables studied are:

1. In adequately reinforced continuous pavements, temperature decreases of more than about 30 degrees below casting temperature tend to increase the deflections due to vertical (wheel) loads. Temperature decreases less than 30 degrees tend toward a slight decrease in deflections.

2. The percentage of mid-depth reinforcement has an influence on maximum deflections due to vertical loads; the maximum deflections vary somewhat inversely with the percentage of reinforcement.
3. Upper surface crack widths vary somewhat linearly with temperature decreases in slabs reinforced with inadequate amounts of welded wire fabric but with adequate splice laps. Pavements with adequate amounts of reinforcement form new cracks during sizable temperature decreases and old cracks do not continue to widen in direct proportion to temperature drop.
4. Maximum active crack widths (due to temperature drops and wheel loads) at the upper and lower surfaces of the slab can be equalized and minimized by proper placement of the steel reinforcement. The results of these laboratory experiments suggest that top and bottom surface active crack widths might be approximately equalized by placement of the fabric about 3/4 of an inch below mid-depth.
5. An increase in the average steel stress at a crack accompanies increased temperature drops (below concrete casting temperature); furthermore the stresses vary somewhat inversely with percentage of longitudinal reinforcement at mid-depth.

6. Vertical loads contribute significantly to stresses in the reinforcement.
7. Reinforcement placed 1-1/2 inches above mid-depth must resist stresses considerably greater than the same amount of reinforcement placed at mid-depth or below.

INTRODUCTION

Research on continuously reinforced pavements already summarized (1) indicates the great interest in this relatively new type of pavement which shows promise of providing smooth riding qualities and low maintenance costs over a long service period. The apparent advantages of this type of pavement design are adequate incentive to additional research directed toward the determination of rational procedures for the design of continuously reinforced pavements.

Field experiments on continuously reinforced pavements have included studies of pavement deflections including crack widths (2, 3, 4, 5, 6) and stresses in the steel reinforcement (2, 4, 5). Pavement deflections and crack widths must be the basis for important design criteria. Likewise steel stresses, since they are repetitive in nature, must be maintained below the endurance limit of the reinforcement.

The recognized purpose of continuous longitudinal reinforcement in pavements is to control the formation of cracks and to hold the cracks tightly closed. Such closed cracks prevent the easy entry of water and soil particles and provide adequate aggregate interlock to transfer the loads and forces across the cracks. After the formation of these fine cracks (7), the pavement is no longer a continuous structural unit but acts as a series of relatively rigid slab segments connected by relatively flexible reinforced cracked sections (8, 9). Stresses in the steel reinforcement are critical at cracks.

Deflections of pavements are closely associated with subgrade "pumping." While not all subgrades are susceptible to pumping, it is obvious that pavement deflections must occur in some magnitude to initiate pumping of those subgrades which are susceptible to such deterioration.

A complete knowledge of the combined effects of temperature changes and wheel loads on reinforcement stresses, slab deflections and crack widths for slabs reinforced with various amounts of steel in various positions and resting on subgrades of various stiffnesses must be obtained in order to establish rational criteria for the design of continuously reinforced pavement slabs.

PURPOSE AND SCOPE OF DISCUSSION

The objectives of this paper are:

1. To report the results of a series of laboratory experiments on simulated continuously reinforced concrete slabs, with emphasis on those results pertaining to slab deflections, crack widths, and stresses in the continuous welded wire fabric reinforcement.
2. To compare the results of these laboratory experiments with reported field data.
3. To arrive at tentative criteria for the design of continuously reinforced pavements as suggested by this study of stresses and deflections (including crack widths) in pavements continuously reinforced with welded wire fabric.

In making use of the results shown in this paper, the limitation imposed by the range of variables introduced in this laboratory should be kept in mind. This range of variables, which is outlined in the following section, will be expanded through the continuation of this research; future results may substantially add to or otherwise alter the findings reported here. One important criterion for the design of continuously reinforced concrete pavements has resulted from the study of crack formation in such pavements (7).

LABORATORY EXPERIMENTS AND RESULTS

Specimens for these experiments were concrete slabs 8 inches thick, 3 feet wide, and 28 feet long,[1] reinforced with welded wire fabric. The controlled variables included in the experiments were percentage of longitudinal reinforcement, position of reinforcement, range of simulated temperature drop after casting of the concrete (longitudinal forces), and magnitude and position of simulated wheel loads. The slabs tested and the magnitude assigned to each variable for the various slabs are summarized in Table 1. The subgrade modulus was held constant at 155-160 pci for the experiments reported here, through the use of a rubber subgrade.

Each slab specimen contained three preformed transverse cracks spaced five feet apart as shown on Fig. 1. Vertical loads were applied at seven locations on the longitudinal centerline of slabs 1 and 2 and at eight locations on slabs 3, 4, and 5, as shown on the same figure.

[1] Details of slab fittings pertinent to the application of loads are described elsewhere (1).

The general procedure for loading the specimens and collecting the data was as follows:

1. A set of strain and deflection readings was taken with no load on the slab. Vertical loads of 5,000 pounds, 10,000 pounds, and 15,000 pounds were then applied at position No. 1 and a set of readings was taken for each load. This procedure was repeated for vertical load positions No. 2 through 8 successively (2 through 7 for slabs 1 and 2).
2. A set of strain and deflection readings was taken with no load on the slab. An initial longitudinal load of 10,000 pounds was applied and a set of readings was taken while holding this longitudinal load constant, the vertical loadings were repeated at positions No. 1 through No. 8 (No. 7, slabs 1 and 2) successively with appropriate data collection, and the loads were then removed.
3. The horizontal load was increased in increments and step 2 was repeated for each increment. In general, increments of 10,000 pounds were used.

As a trial, the loading sequence was altered slightly for Slab 2. This slab was tested continuously without removing the longitudinal load after each set of vertical loads was applied. The longitudinal load was simply increased by the 10,000-pound increment before the next set of vertical loads was applied.

During the entire loading sequence, measurement of concrete strains and crack widths was made at the upper surface of each slab.

Steel plugs had been embedded in the surface in the test area of each slab at ten-inch intervals as shown on Fig. 2. Gage holes were drilled in these plugs and a ten-inch Whittenmore strain gage was used to make surface strain and crack width measurements. For an uncracked gage length the average unit strain was taken as the change in gage length divided by ten. When a transverse crack occurred between two plugs, it was assumed that the total change in that gage length was due to a change in the crack width. This continuous set of gage lengths thus made it possible to determine the over-all change in length of the test region due to various combinations of horizontal and vertical loads.

The longitudinal tensile loads simulated the effect of temperature drops. Correlation of the magnitude of longitudinal load to temperature drop was determined by calculations. The over-all increase in length of the central test region of a slab due to longitudinal load, as determined by the surface strain readings, was equated to the decrease in length of the same span of reinforced concrete due to a temperature drop, Δt. Thus the condition of effective full restraint against longitudinal movement in a continuously reinforced slab away from the end regions was assumed.

In equation form

$$e = \alpha L \Delta t$$

or

$$\Delta t = \frac{e}{\alpha L}$$

where

e = elongation (inches) of central test region

L = length (inches) of central test region

α = coefficient of linear contraction — assumed to be 0.000006 in./in./degree F. for both steel and concrete.

Δt = temperature drop (degrees F.)

Further details concerning the calculations necessary for the correlation of longitudinal forces and temperature decrease may be found elsewhere (7).

Vertical Deflections

It is generally agreed that continuously reinforced concrete pavements without joints are less susceptible to the damaging effects of pumping than rigid pavements of other current designs, but that under certain conditions of subgrade type and traffic they are not immune from pumping action at the free edge of the pavement. The possibility of such pumping may be reduced through proper pavement design to control the vertical movements of the slab under vertical loading.

Vertical deflections of each slab were measured at nine stations as shown on Fig. 1. To indicate the effects of vertical loads on slab deflections, each slab was assumed to be straight when subjected to the various longitudinal loads with no vertical loads acting. The additional deflections due to five-, ten-, and fifteen-kip vertical loads placed at each of the load positions were then

measured. A series of graphs similar to that shown on Fig. 3 was drawn for each slab subjected to a full range of the longitudinal loads which simulated temperature drops. These served as a basis for determining average values of maximum deflections of preformed cracks and for obtaining the magnitudes of angle changes at cracked sections of the slabs.

A graphical indication of the influence of temperature drop and percentage reinforcement on maximum vertical deflections due to 15-kip wheel loads is given by Fig. 4. The data points shown are the average of the maximum deflections of the three preformed cracks when each was loaded in turn by the 15-kip simulated wheel load, with the slab subjected to various longitudinal loads (temperature drops). It is seen that the three slabs which contained different percentages of longitudinal reinforcement sustained deflections ranging from 0.07 to 0.10 inches in magnitude throughout the total range of simulated temperature drops. At the greatest temperature drop, Slab 3 with the greatest amount of longitudinal reinforcement (0.450 percent) showed about 18 percent less deflection than Slab 2 (0.300 percent steel) and about 26 percent less deflection than Slab 1 (0.154 percent steel).

The influence of vertical location of the reinforcement on deflections due to wheel loads can be seen in Fig. 5. Of the three slabs which contained the same percentage of steel at three different locations, Slab 5 with its reinforcement 1-1/2 inches above mid-depth

allowed less deflections than the slab reinforced at mid-depth; furthermore the slab reinforced at 1-1/2 inches below mid-depth allowed more deflection than the other two, throughout the full range of 100 degrees of temperature decrease. This result was undoubtedly influenced by the presence of the double percentage of steel at the two outside preformed cracks, introduced by lapping of the fabric at these two cracks.

Downward deflections under simulated wheel loads were usually accompanied by some negative deflection (upheaval) at adjacent cracks. Thus under a moving wheel load, each crack section was subjected to vertical movements greater in magnitude than the maximum downward deflection. The total vertical movement of cracks is probably more indicative of the possibility of initiating pavement "pumping" than is maximum downward deflection of cracks.

Fig. 6 displays the influence of temperature drop and percentage reinforcement on total vertical movements due to 15-kip wheel loads. The data for this graph were also obtained by averaging the total vertical movements of the three preformed cracks. It can be seen that Slab 3 with its 0.450 percent longitudinal reinforcement offered more restraint against total vertical movement at temperature drops greater than 40 degrees than Slabs 1 and 2 which are considered (7) to have been under-reinforced. The increase in total vertical movements of cracks with increased temperature drops was negligibly small in Slab 3, but was of significance in Slabs 1 and 2.

The effect of position of 0.450 percent longitudinal reinforcement on total vertical movement of cracks is shown on Fig. 7. In this respect, it appears that there is negligible basis for choice between mid-depth and above-center reinforcement, both having furnished some more restraint against total vertical movements throughout the greater portion of temperature drops than the low-level reinforcement.

Crack Widths

All engineers interested in design or research on continuously reinforced concrete pavements are vitally concerned with studies of crack formation and crack widths in the concrete slabs. It is generally recognized that the function of the longitudinal steel is to maintain the cracks, which must necessarily form, in a tightly closed condition so that fine grained soils cannot enter the cracks from either the top or the bottom. In discussing the probability of blowups in continuously reinforced pavements, the late W. P. Woolley (10) cited progressive spalling due to the accumulation of dirt in cracks, from the top and perhaps also from the bottom of the slab, as the first step toward blowups. He reasoned that after awhile, as a result of spalling, the compression across a crack, which develops with rising temperature, must be carried by a progressively smaller section of concrete than the original full depth. Blowups then occur as a natural consequence.

Thus it is generally agreed that in properly designed continuously reinforced pavements, the cracks are held so tight that soil cannot get into them and spalling does not occur to an appreciable extent. Therefore, one key to optimum design is the control of crack widths.

In the slabs tested, the center preformed crack carried a single layer of welded wire fabric. Splices were placed at (or near, in Slab 1) the two outer preformed cracks--15- and 16-inch laps in Slab 1, and 2-foot and 4-foot laps in Slabs 2 through 5. The center crack widths were considered to be representative of most cracks which would occur in a pavement slab and were therefore studied in detail; however, it was found that the splices influenced somewhat the widths of adjacent cracks.

Crack width data obtained from the upper surface strain plugs with the slabs subjected to longitudinal loads (temperature drops) only is sampled on the graphs of Fig. 8. This shows the variation in the upper surface center crack widths with temperature drops for Slabs 1, 2, and 3. The center crack openings for Slab 1 were relieved by an early semi-yielding of the lap splices at the adjacent cracks. This accounts for the small crack openings plotted for Slab 1 in the lower range of temperature decrease. Slab 3, with its 0.450 percent longitudinal reinforcement developed two additional cracks at an early 16 degrees temperature change; this relieved the center crack of further opening over a long range of temperature drop. In fact,

no appreciable increase in this center crack width resulted until a total temperature change of about 90 degrees. Except for the results of Slab 1, which were effected by the semi-yielding of the outer cracks, it is seen that, through the greater range of temperature drops, crack widths varied somewhat inversely with percentage of longitudinal reinforcement.

The influence of temperature drops and position of reinforcement on upper surface crack widths are shown in Fig. 9. Again the beneficial effects of early formation of additional cracks is seen. The center crack of Slab 3, which had 0.450 percent steel at mid-depth and which developed the two additional cracks at 16 degrees decrease, was maintained more tightly closed than the center crack of either Slab 4 with the same steel below mid-depth or Slab 5 with its steel above mid-depth. It is also seen that the center crack of Slab 4 closed somewhat after the formation of six additional cracks in or near the test region of the slab.

In the design of a continuously reinforced pavement, the upper surface crack widths due to temperature changes alone are of less importance than top and bottom surface maximum crack widths due to temperature changes and wheel loads. As the wheel loads move along the pavement the slab deflects and the top and bottom crack widths vary over significant ranges. Water and soil can work into cracks at the upper surface under the action of gravity and at the bottom surface under the pressure developed between the slab and the subgrade.

Thus it is important to minimize active crack widths at both top and bottom surfaces of the slab.

The laboratory experiments involved measurement of the variation of upper surface crack widths with temperature changes and wheel loads for those slabs reinforced by steel at mid-depth. In addition, crack widths on the sides of the slabs at the elevation of the steel were measured on the slabs reinforced with steel below and above mid-depth. Good estimates of bottom surface crack widths were obtained by calculations. For slabs reinforced with steel below (or above) mid-depth, top surface and side crack width data for temperature changes alone indicated cracks increasing in width with the distance from the steel as shown exaggerated in Fig. 10a. The measured crack width at the elevation of reinforcement is δ_r. The upper surface crack width ($\delta_r + \delta_i$) was also measured. It was assumed that the increase in crack width both above and below the reinforcement was linear. Thus the crack width δ_{ob} at the bottom surface due to temperature alone was

$$\delta_{ob} = \delta_r + \delta_i \frac{b}{a}$$

Applications of vertical loads changed the upper and lower crack widths appreciably. From the deflection diagrams (similar to Fig. 2), angle changes due to 15-kip wheel loads were scaled accurately for the center preformed crack for each horizontal load on each slab. These angle changes were assumed to be centered at the reinforcement in the cracked section. When multiplied by the distance of the

reinforcement from the lower surface, they gave the additional bottom surface crack widths, δ_α, due to the angle changes induced by the wheel loading. Thus, the total bottom surface crack width, δ_b, due to temperature change and wheel loading is (Fig. 9b)

$$\delta_b = \delta_{ob} + \delta_\alpha = \delta_r + \delta_i \frac{b}{a} + \alpha b$$

For the special case of mid-depth reinforcement, the ratio $\frac{b}{a}$ is equal to unity and the first two terms of the bottom surface crack width (the last member of the equality) are the same as the top surface crack width due to temperature drops alone. That is to say, for mid-depth reinforcement it is assumed that due to temperature changes alone, top surface crack widths are equal to bottom surface crack widths.

Fig. 11 outlines the influence of temperature decrease and position of steel on maximum upper and lower surface crack widths due to 15-kip wheel loads. A comparison of Figs. 9 and 11 shows that wheel loads did have appreciable effect on the magnitudes of maximum top surface crack widths. Fig. 11 shows quite clearly that bottom surface crack widths were considerably greater than top surface crack widths in simulated continuous pavement slabs reinforced at mid-depth and above, while top surface crack openings were greater than bottom surface crack openings in the slab reinforced at 1-1/2 inches below mid-depth. A study of these curves suggests that top and bottom surface active crack widths might be approximately equalized by placement of the steel about three-fourths of an inch below mid-depth.

Steel Stresses

In continuous concrete pavements reinforced with welded wire fabric, the longitudinal wires are subjected primarily to uniaxial tensile or compressive stresses. Although this longitudinal steel does transfer a portion of the loads across cracks in the concrete, its primary contribution is made by holding the cracks tightly closed so that concrete aggregate interlock resists the greater portion of the shear forces at a crack.

To determine the stresses in the longitudinal wires of the welded wire fabric at cracks, several SR-4 type A-7 electrical strain gages were applied to the wires at each of the preformed cracks as previously described (1). Gages were also placed on the longitudinal wires between cracks to determine the role of the reinforcement in unbroken segments of the concrete. Strain gage readings were taken during the experiments in the same sequence as the deflection and crack width measurements. Strains were multiplied directly by the modulus of elasticity to obtain the steel stresses.

Significant differences were obtained between the steel stresses at cracks and those farther away than one transverse wire from the cracks; the latter were always quite small while the stresses at the cracks were of such magnitude as to require special attention in the design of a continuously reinforced concrete pavement.

Variations in steel strains, some as great as twenty percent from the average, were obtained from the several gages at a single

crack, under a given load arrangement. These variations were probably due to unequal loss of bond as a result of strain gage waterproofing, and normal variations in anchorage furnished by the welded transverse wires. Furthermore, the irregular shape of some of the cracked transverse sections of the slabs may have caused uneven pressures to develop in the concrete at cracks under vertical loads. Obviously one cannot predict exact values of either maximum or average stresses in the wires at cracks; however, it is practically as important to know the order of magnitude of stresses as to know the exact values. Average values serve as an adequate basis for comparison of the various percentages and positions of reinforcement in arriving at optimum pavement design.

To obtain representative values of steel stresses at cracks, the eight strain gage measurements at the center crack were averaged. Fig. 12 shows the variation in longitudinal steel stress due to the simulated temperature changes only, for the various percentages of reinforcement. These curves show, in general, an increase in steel stress with increased temperature drops and, except for Slab 1 in which the adjacent cracks semi-yielded, show a trend in favor of an increase in percentage of reinforcement for temperature drops greater than 35 degrees. The position of the fabric reinforcement had considerable influence on the maximum steel stresses at cracks due to temperature changes alone. This can be seen in Fig. 13. The mid-depth reinforcement of Slab 3 was subjected to a little less stress than the lowered reinforcement of Slab 4 at temperature drops greater than 35 degrees and to considerably less stress

than the high reinforcement of Slab 5 at all temperature ranges. The stress relief induced in Slab 3 by the formation of two additional cracks at 16 degrees temperature drop is apparent.

Wheel loads contribute significantly to the stresses in the reinforcement of continuously reinforced pavements. Fig. 14 shows the combined effect of 15-kip wheel loads and temperature decreases on the steel stresses at the center cracks for the various percentages of longitudinal steel. This set of curves shows definitely the inadequacy of the 0.150 and 0.300 percent steel of Slabs 1 and 2 respectively. The 0.450 percent reinforcement of Slab 3 appears adequate in regard to stresses. Here, also, the influence of the early formation of additional cracks in Slab 3 was beneficial. The position of the reinforcement had considerable influence upon the maximum steel stresses at cracks due to temperature changes and 15-kip wheel loads. In Fig. 15 it is seen that Slab 3, with its reinforcement at mid-depth was subjected to slightly less steel stresses than Slab 4 with its reinforcement 1-1/2 inches below mid-depth. Both Slabs 3 and 4 were subjected to considerably less steel stresses than Slab 5 with its reinforcement 1-1/2 inches above mid-depth. The early formation of the two additional cracks in the test region of Slab 3 undoubtedly contributed to sufficient stress relief to make the steel stresses in Slab 3 fall below those of Slab 4. One might normally expect the resulting curve for Slab 3 to fall between the curves for Slabs 4 and 5, at least in the region of large temperature decreases.

Additional details concerning the results of these experiments may be found in research reports written by William E. Witzell (18) and James E. Houmard (19).

CORRELATION OF RESULTS OF LABORATORY EXPERIMENTS WITH REPORTED FIELD TESTS

Field experiments with continuously reinforced concrete pavements have included a limited number of test pavements reinforced with welded wire fabric. The Indiana (Stilesville) test road (11) included two test sections 310 feet long reinforced with fabric to provide 0.42 percent longitudinal steel placed at 2-1/2 inches below the top surface of a standard 9-7-9 inch thickened edge pavement. Other shorter sections were also included. The New Jersey test road (12) included two sections 5430 and 5130 feet long reinforced with fabric giving 0.90 and 0.72 percent longitudinal steel in slabs 8 and 10 inches thick, respectively. That fabric was placed in two layers by the strike-off method.

Very little, if any, data on pavement deflections due to wheel loadings were produced by the reported field experiments on continuously reinforced pavements. Investigators (13) have experienced difficulties in establishing adequate datum planes for such field measurements, due to the compressibility of considerable depth of subgrade. Field experiments on continuous reinforcement of pavement slabs have, in general, been directed toward other more pressing problems.

The variation of widths of crack openings due to temperature changes has been studied in several of the field experiments. At the end of ten years of service, the Indiana (Stilesville) test road (14) showed crack widths ranging from 0.02-0.06 inches with an average of 0.038 inches in the lane reinforced with 0.45 percent steel and carrying light traffic. These crack openings were measured in the fall of the year when the mean pavement temperature was 58-60 degrees F. Those measurements were made in such a manner as to include raveling and rounding of the edges of the concrete at cracks. Widths of cracks measured at mid-depth on the edge face of the pavement to exclude raveling and rounding showed real widths of less magnitude than the upper surface crack widths. These measurements, made with a microscope in the fall when the mean pavement temperature was 73-74 degrees F., showed crack widths ranging between 0.007 and 0.010 inches in the same section of pavement mentioned above. Similar data for other percentages of reinforcement showed that the crack widths, for a given temperature, increased with a decrease in the percentage of longitudinal reinforcement.

The three year performance report on the Illinois (15) continuously reinforced pavement stated that 7-inch and 8-inch thick slabs reinforced with 0.3, 0.5, 0.7, and 1.0 percent steel had developed transverse cracks ranging in width from 0.007-0.021 inches by August, 1950. Measurements taken after three years of service from the New Jersey (16) experimental pavement showed a maximum crack

width of 0.019 inches and an average crack width of 0.015 inches in the outside lane of an 8-inch pavement, at a net temperature drop of 31 degrees. This pavement was longitudinally reinforced with 0.90 percent steel.

Thus, although no direct correlation can be made between the crack widths obtained in the laboratory experiments and the various field experiments, it is seen that the crack width measurements made in the laboratory were in the same order of magnitude as those observed in the field.

Changes in crack widths with passage of wheel loads have not been reported from the field experiments. Thus no correlation can be made between the laboratory and field experiments in this important phase of the experiments.

Reinforcement steel stresses have been measured in the Illinois (15), California (17), and Pennsylvania (5), experiments. Stresses as great as 62,000 and 42,000 psi were reported for the Illinois experiment for 7-inch and 8-inch slabs reinforced with 0.7 percent steel. Stresses as great as 50,000 and 80,000 psi were reported from the California experiment at the end of six months after casting the concrete in 8-inch slabs reinforced by 0.62 and 0.50 percent steel, respectively. Stresses exceeding the yield strength of the steel were reported at two months and three months after casting the pavement at York, Pennsylvania. This pavement contains 0.50 percent longitudinal steel.

The California report (17) contained the following statements in regard to reinforcement steel stresses which are of special interest:

> At early ages (less than 3 months) the readings on pairs of SR-4 gages opposite each other on the same reinforcing bar were in agreement within 10 percent. There was, however, a noticeable increase in the variations in readings at 3 months and at 6 months.

As a result of the laboratory experiments, it is believed that such variations are to be expected as a result of unequal stress build-up due to temperature changes and wheel loads rather than as a direct result of the passage of time.

It can be seen that the several field experiments yielded a variety of magnitudes of crack widths and stresses in the various types of reinforcement due to temperature changes. These variations can be attributed to such influencing variables as subgrade stiffness, concrete casting temperatures, and subsequent moisture conditions. The crack widths and steel strains reported for the field experiments were on the same order of magnitude as those obtained in these laboratory experiments.

Data on crack widths and steel stresses due to wheel loads as well as temperature changes have not been reported from the several experiments.

DESIGN CRITERIA

A study of laboratory data on vertical deflections, crack widths, and reinforcement steel stresses, on an individual basis, suggests the following criteria for the design of continuously reinforced pavements:

(1) For the temperature range between the temperature of casting of the concrete and the freezing temperature of the subgrade, the total vertical movement composed of downward deflection under wheel loads and upheaval as the loads move away should be minimized as nearly as practicable.

(2) For the same practical temperature range delineated in criterion 1, the upper surface and lower surface crack widths should be considered equally important and the maximum active crack widths due to wheel loads as well as temperature changes at both the upper and lower surface should be minimized as nearly as practicable.

(3) For the practical temperature range, the maximum reinforcement steel stress (average) due to temperature changes and wheel loads should be maintained below the yield strength of the steel with as great a margin as is economically feasible.

In general, all three of these design criteria cannot be completely satisfied by a single choice of amount and position of reinforcement.

Furthermore, economic considerations may place practical restrictions on the designer in his choice of concrete thickness and steel reinforcement for continuous pavements which might make these criteria unattainable; thus the criteria must serve as a guide for compromise in the choice of design characteristics of continuously reinforced pavements.

A previous study (7) of formation of cracks in continuous pavements has suggested another criterion which should be satisfied along with the three listed above. It can be summarized by the following statement:

(4) Sufficient amount of longitudinal reinforcing steel must be provided to maintain all transverse cracks in a tightly closed condition without adverse effects on the concrete. For mid-depth reinforcement, this condition is met when increasing longitudinal forces caused by temperature drops, in combination with live loads, tend to cause additional cracks to form rather than to cause excessive opening of existing cracks.

The above four criteria can be applied in judging the relative merits and acceptability of the five slabs included in the laboratory experiments. It must be remembered, however, that the experiments reported here have included to date only slabs 8-inches thick resting on a subgrade having a modulus of 160 pci. Thus the optimum pavement design may not be represented among these slabs. Table 2 summarizes the application of the four criteria to the slabs tested.

Examination of the ratings in Table 2 reveals the general inadequacy of the light reinforcement in Slabs 1 and 2. Slab 5 with its reinforcement 1-1/2 inches above mid-depth is rated inadequate because of excessive lower surface active crack widths and because of the high steel stresses. Slab 3 with its reinforcement at mid-depth proved to be somewhat better in every respect than Slab 4 with its reinforcement 1-1/2 inches below mid-depth except for the item of formation of cracks. Thus, from the five specimens tested to simulate 8-inch thick continuous concrete pavements reinforced with welded wire fabric and resting on subgrades having a modulus of 160 pci, reinforcement with 0.450 percent longitudinal steel placed at mid-depth appears to represent the most economical design and best performance. However, if additional slabs were tested, perhaps 0.450 percent reinforcement placed about three-fourths of an inch below mid-depth might prove advantageous.

CONCLUSIONS DRAWN FROM LABORATORY RESEARCH

As a result of these laboratory experiments on continuous pavements reinforced with welded wire fabric, and within the limitations imposed by the range of variables studied, the following conclusions are drawn:

1. In adequately reinforced continuous pavements, temperature decreases of more than about 30 degrees below casting temperature tend to increase the deflections due to

vertical (wheel) loads. Temperature decreases less than 30 degrees tend to cause slight decrease in deflections.

2. The percentage of mid-depth reinforcement has an influence on maximum deflections due to vertical loads; the maximum deflections vary somewhat inversely with the percentage of reinforcement.

3. Total vertical movements (downward deflection plus upheaval) of the pavements due to live loads vary with temperature changes and percentage of reinforcement much the same as deflections.

4. Total vertical movements of the slabs reinforced at mid-depth and above are about the same; both are of less magnitude than the total movement of the slab reinforced below mid-depth.

5. Upper surface crack widths vary somewhat linearly with temperature decreases in slabs reinforced with inadequate amounts of welded wire fabric, but with adequate splice laps. Pavements with adequate amounts of reinforcement form new cracks during sizable temperature decreases and old cracks do not continue to widen in direct proportion to temperature drop.

6. The upper surface control of crack widths due to temperature changes alone appears to be accomplished the best by mid-depth reinforcement.

7. Maximum active crack widths (due to temperature drops and wheel loads) at the upper and lower surfaces of the slab can be equalized and minimized by proper placement of the steel reinforcement. The results of these laboratory experiments suggest that top and bottom surface active crack widths might be approximately equalized by placement of the fabric about three-fourths of an inch below mid-depth.

8. Significant differences exist between the steel stresses at cracks and those farther away than one transverse wire from the cracks; the latter are quite small while the stresses at cracks are of such magnitude as to require special attention in the design of a continuously reinforced concrete pavement.

9. Variations in steel strains (and stresses), some as great as 20 percent, exist among the several longitudinal wires of the fabric at a single crack, under given sizable temperature changes and live loads.

10. An increase in the average steel stress at a crack accompanies increased temperature drops (below concrete casting temperature); furthermore the stresses vary somewhat inversely with percentage of longitudinal reinforcement at mid-depth.

11. Position of reinforcement influences the steel stresses at cracks due to temperature drops alone. Reinforcement placed 1-1/2 inches above mid-depth is subjected to stresses considerably greater than that placed at mid-depth or below.

12. Vertical loads contribute significantly to stresses in the reinforcement.

13. An increase in the percentage of steel placed at mid-depth is accompanied by a decrease in the average steel stress at a crack due to a given temperature decrease and live load.

14. Reinforcement placed 1-1/2 inches above mid-depth must resist stresses, due to temperature drops and live loads, considerably greater than the same amount of reinforcement placed at mid-depth or below.

15. These laboratory experiments yield results pertaining to crack widths and steel stresses which are on the same order of magnitude as those reported from field experiments, although exact conditions of any one field test are not duplicated in the laboratory.

16. Three criteria are suggested as guides in the choice of design characteristics of continuous pavements. These criteria which are supplemented by one derived elsewhere (7), are as follows:

(1) For the temperature range between the temperature of casting of the concrete and the freezing temperature

of the subgrade, the total vertical movement composed of downward deflection under wheel loads and upheaval as the loads move away should be minimized as nearly as practicable.

(2) For the same practical temperature range delineated in criterion 1, the upper surface and lower surface crack widths should be considered equally important and the maximum active crack widths due to wheel loads as well as temperature changes at both the upper and lower surface should be minimized as nearly as practicable.

(3) For the practical temperature range, the maximum reinforcement steel stress (average) due to temperature changes and wheel loads should be maintained below the yield strength of the steel with as great a margin as is economically feasible.

17. Application of the four suggested design criteria indicates that Slab 3 simulating a continuous pavement reinforced with 0.450 percent longitudinal steel at mid-depth was the best of those tested. Reinforcement at 1-1/2 inches below mid-depth rated second best. Perhaps additional experiments might prove that 0.450 percent reinforcement placed about three-fourths of an inch below mid-depth might prove advantageous.

ACKNOWLEDGEMENTS

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TABLE 1

SPECIMEN CHARACTERISTICS

Slab No.	Reinforcement[1]	Percent Reinforcement	Position of Reinforcement below top	Reinforcement[3] Ultimate Strength, psi	Concrete Compressive Strength, psi
1	WWF 6 x 12 0/3	0.154	4 inches	93,400	5360
2	WWF 6 x 12 00000/0	0.300	4 inches	80,400	4720
3	WWF 4 x 12 00000/0	0.450	4 inches	80,400	4620
4	WWF 4 x 12 00000/0	0.450	5-1/2 inches	80,400	4320
5	WWF 4 x 12 00000/0	0.450	2-1/2 inches	80,400	4450

[1] WWF is abbreviation for welded wire fabric.

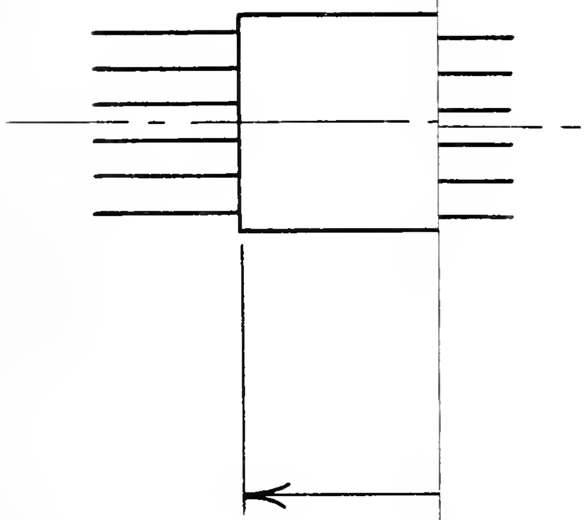
[3] Section 4(a) of ASTM Specification A82-34 for Cold Drawn Steel Wire for Concrete Reinforcement specifies yield stress to be 0.8 ultimate tensile strength. Section 4(d) states that "the yield point shall be determined by the drop of the beam or halt in the gage of the testing machine. In case no definite drop of the beam or halt in the gage is observed until final rupture occurs, the test shall be construed as meeting the requirement for yield point in Paragraph (a)." Thus, while the wire reinforcement had no definite yield point, it satisfied the specification. Specification A82-34 has been in effect during the entire time of this project.

TABLE 2

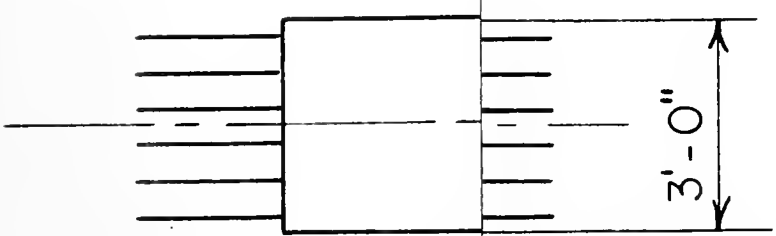
SPECIMEN RATINGS

Slab No.	Percent Longitudinal Reinforcement	Position of Reinforcement	Rating* - According to Criteria			
			1. Vertical Movement	2. Crack Width	3. Steel Stress	4. Crack Formation
1	0.154	Mid-depth	D	D	D	D
2	0.300	Mid-depth	C	D	D	C
3	0.450	Mid-depth	A	A	A	B
4	0.450	1-1/2 in. below M.	B	B	B	A**
5	0.450	1-1/2 in. above M.	A	D	C	A**

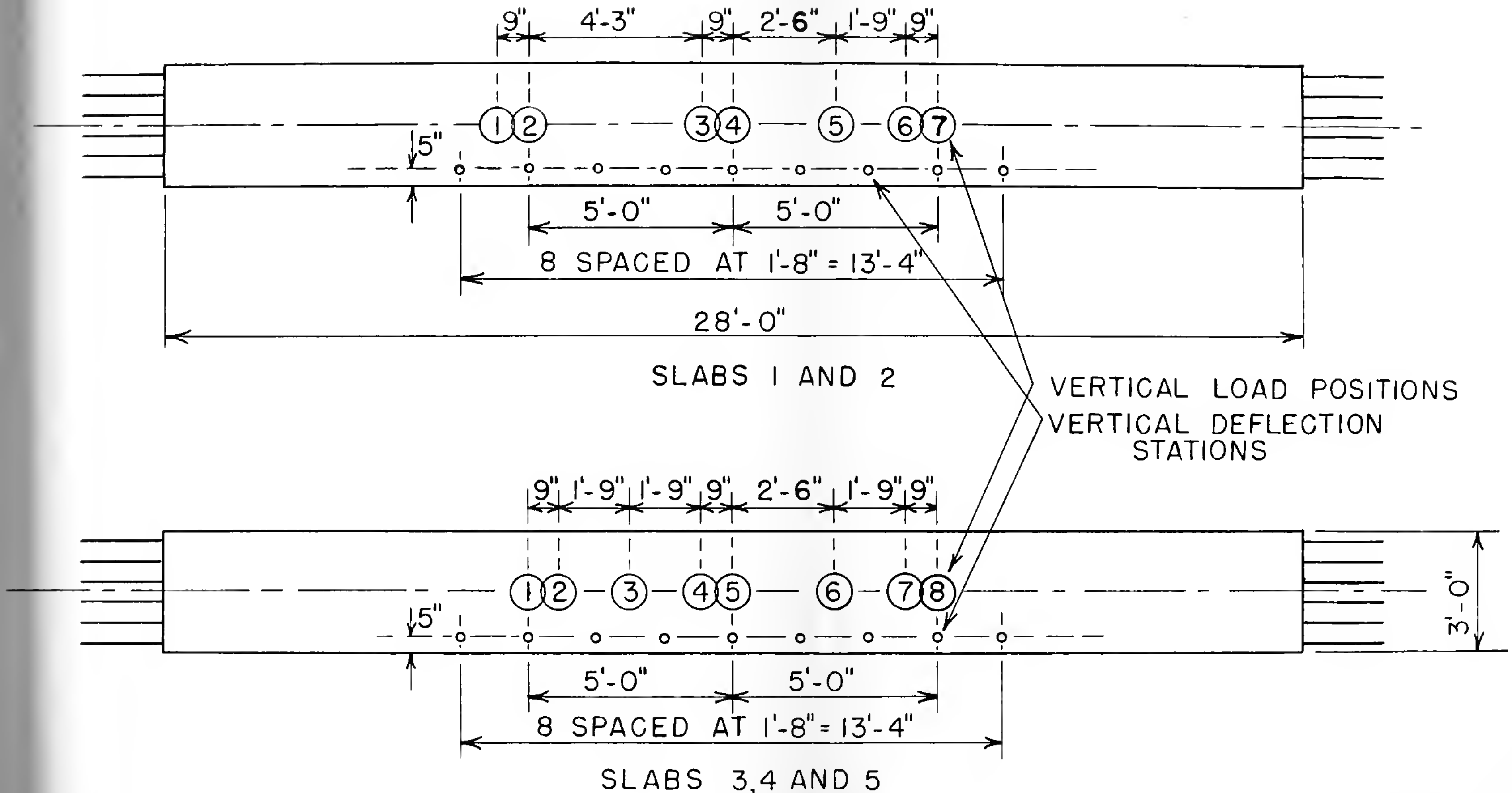
* Rating Definitions:
A - satisfies criterion completely.
B - satisfies criterion nearly completely in comparison with other specimens.
C - satisfies criterion partially - less than other specimens.
D - Criterion rules out the design completely.
** - Criterion not yet intended to apply to slab reinforcement placed other than at mid-depth.



SITIONS
ON

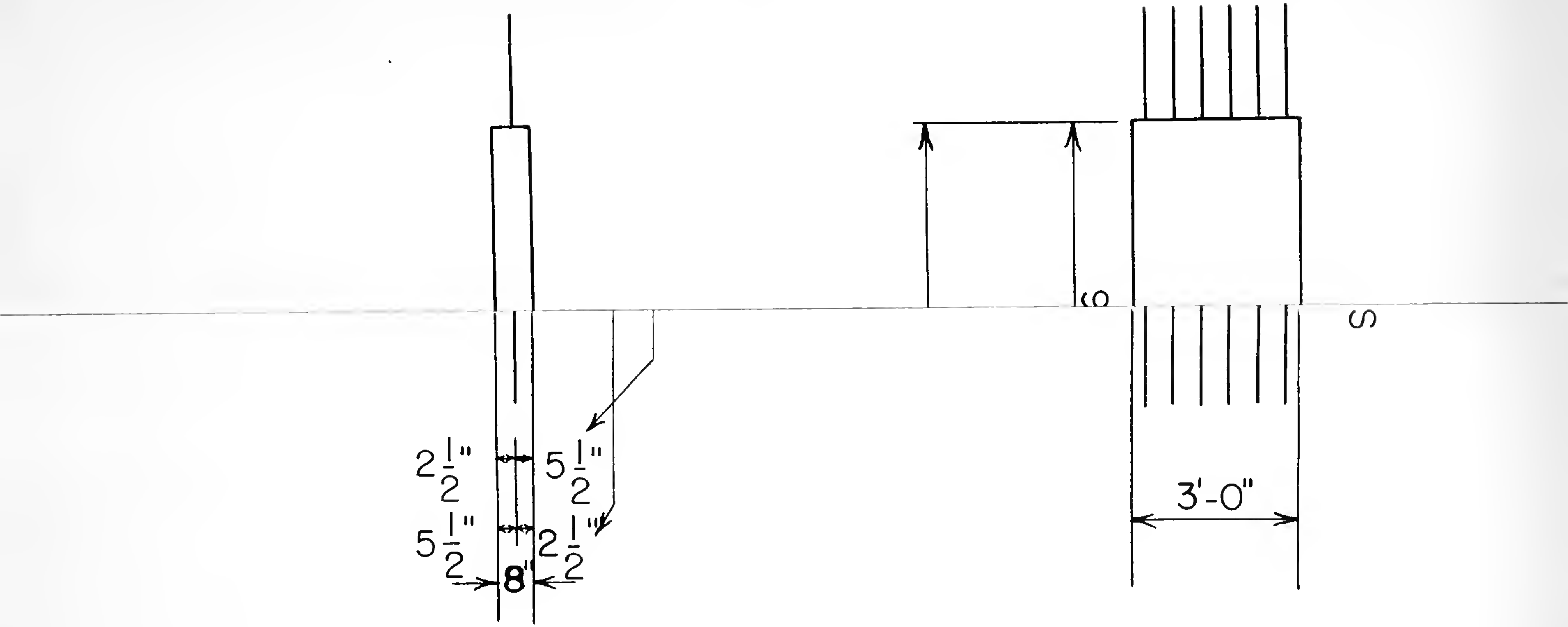


POSITIONFLECTIONS



POSITION OF VERTICAL LOADINGS AND MEASUREMENTS OF VERTICAL DEFLECTIONS

FIG. 1



$2\frac{1}{2}$"
$5\frac{1}{2}$"
$5\frac{1}{2}$"
$2\frac{1}{2}$"
8"
3'-0"
S

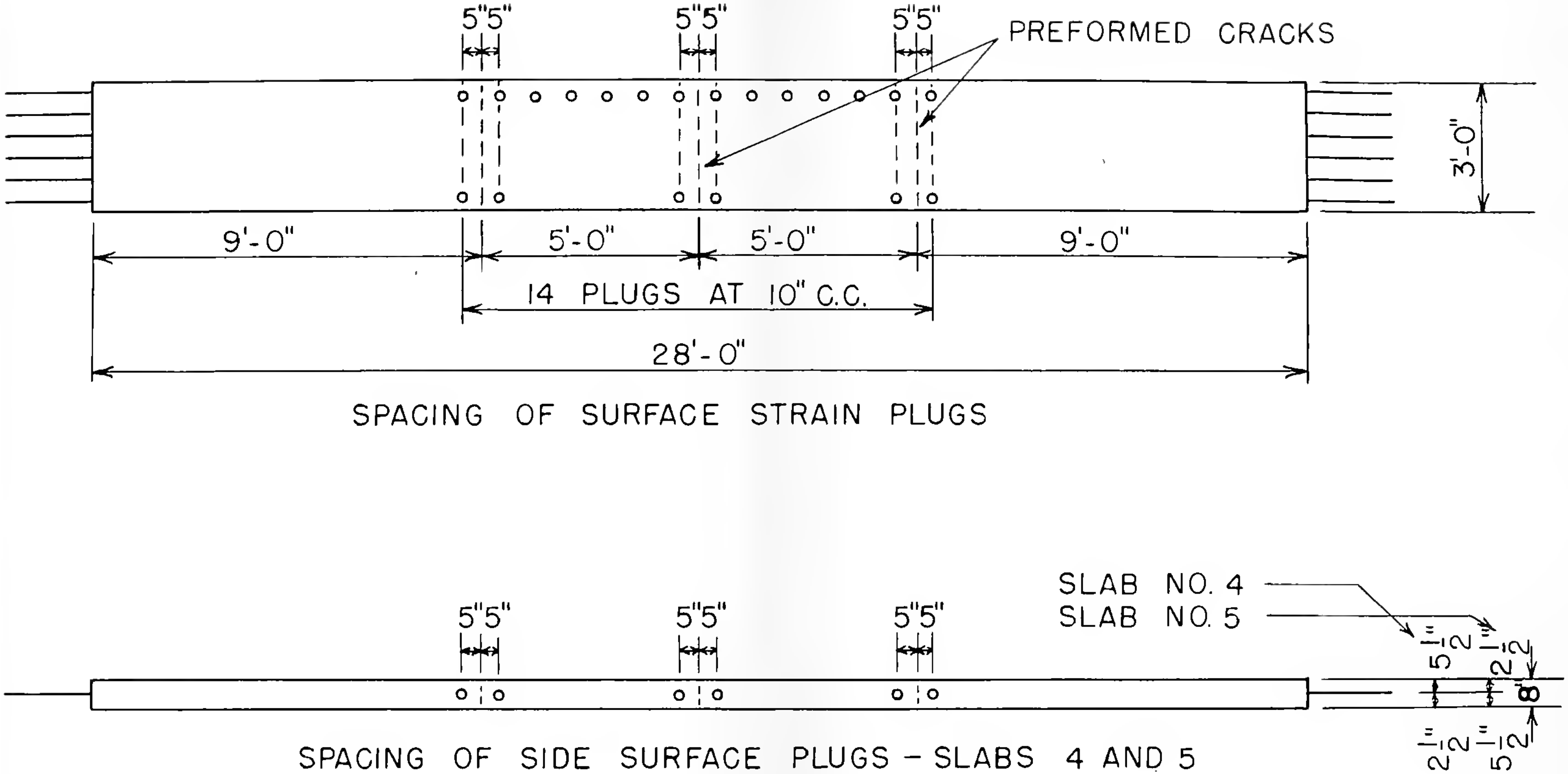
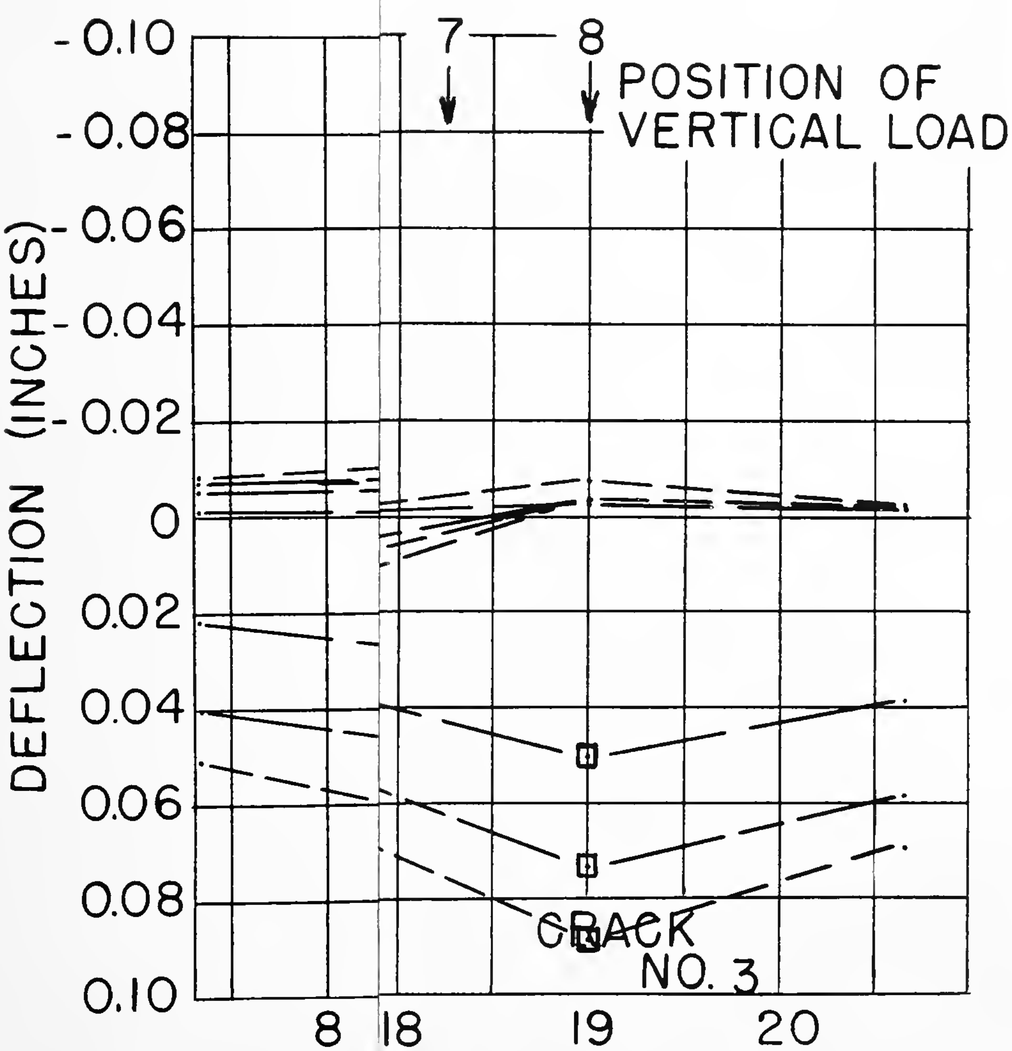

5"5"
5"5"
5"5"
PREFORMED CRACKS
3'-0"
9'-0"
5'-0"
5'-0"
9'-0"
14 PLUGS AT 10" C.C.
28'-0"
SPACING OF SURFACE STRAIN PLUGS
SLAB NO. 4
SLAB NO. 5
5"5"
5"5"
5"5"
8"
SPACING OF SIDE SURFACE PLUGS - SLABS 4 AND 5

FIG. 2



DEFLECTION (INCHES)
-0.10
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.10
7
8
POSITION OF VERTICAL LOAD
CRACK NO. 3
8
18
19
20

F

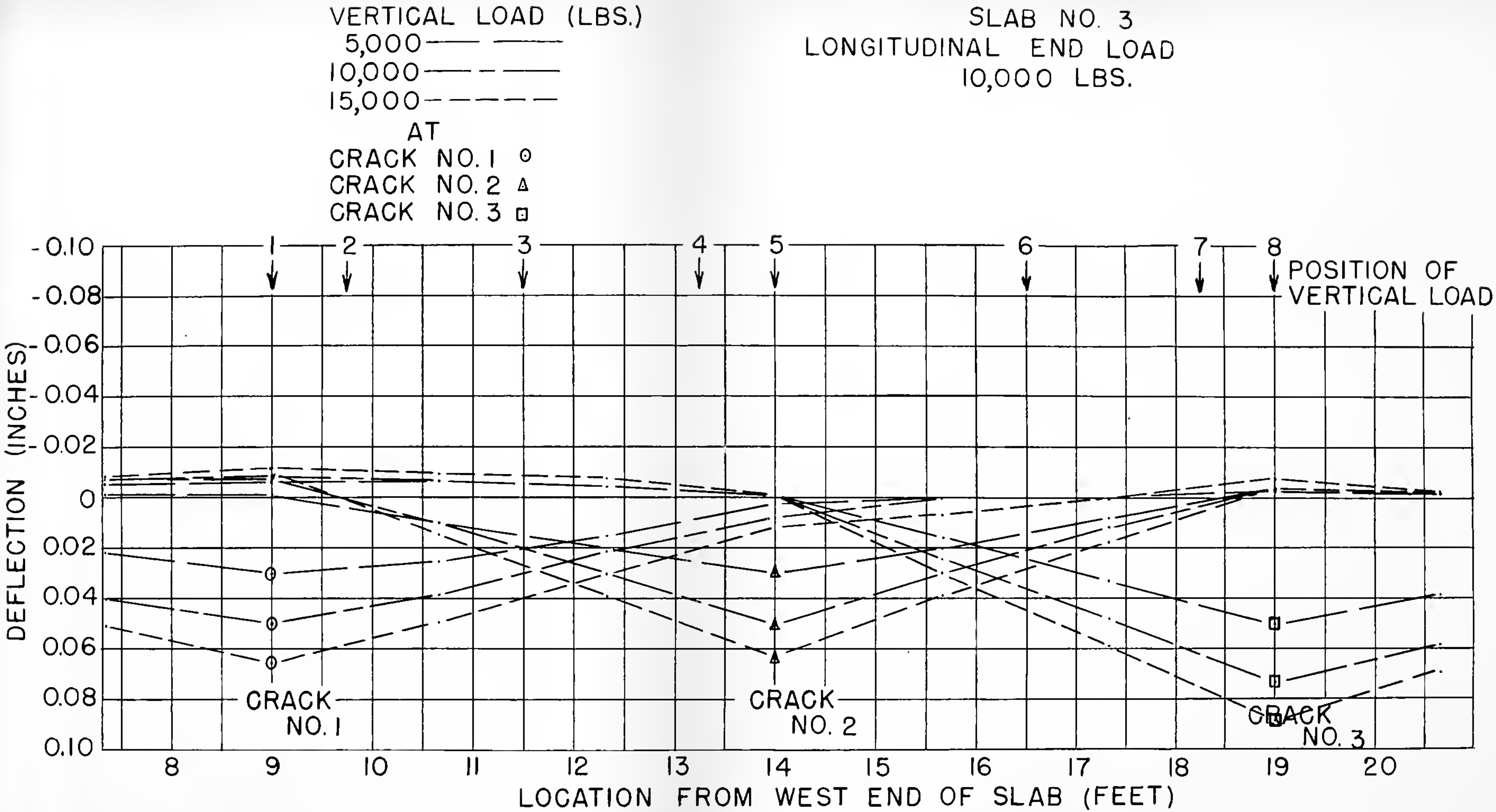


FIG. 3 - VERTICAL DEFLECTION OF SLAB DUE TO COMBINED LOADING AT A CRACK

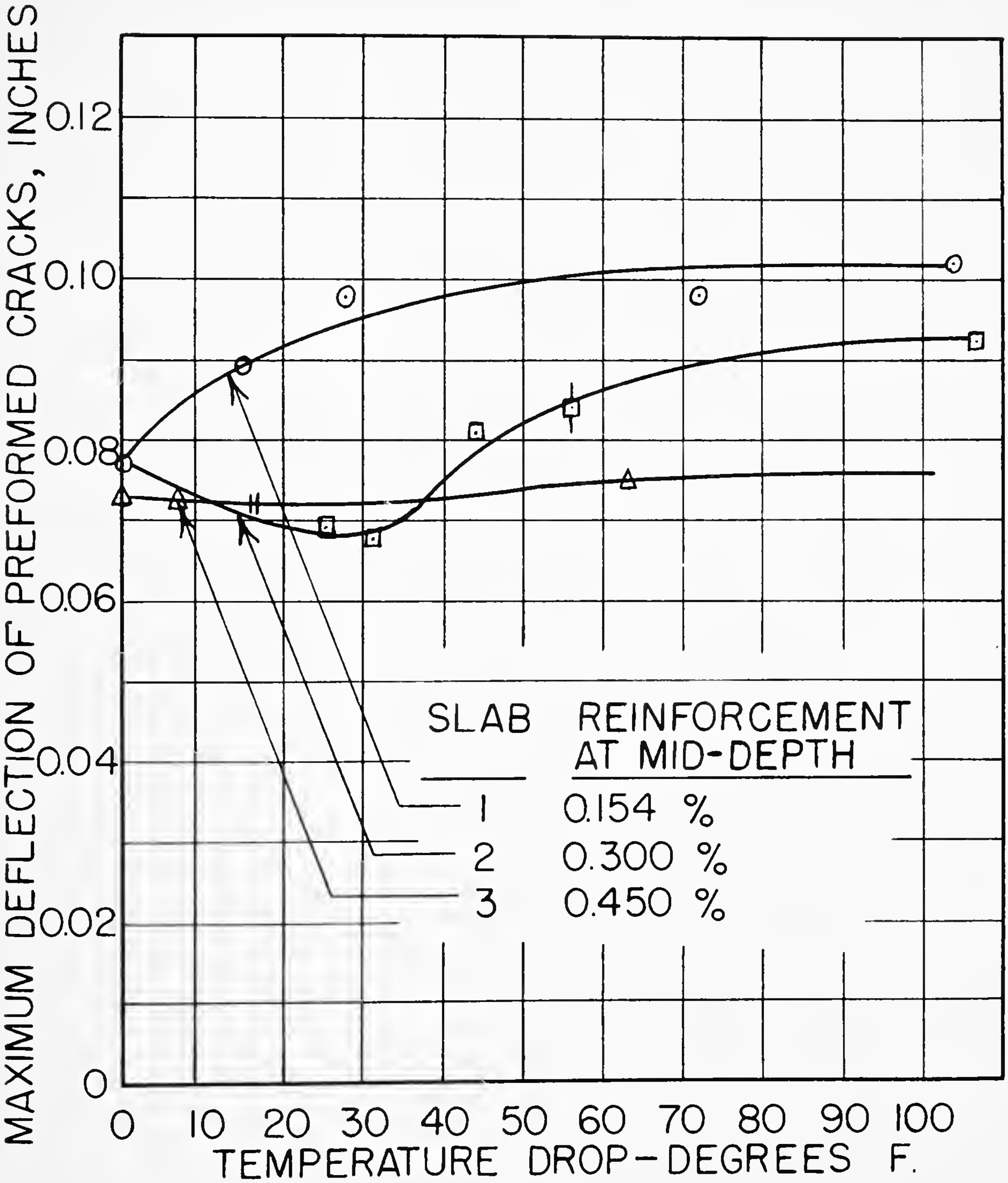


FIG. 4 - INFLUENCE OF TEMPERATURE DROP AND PERCENTAGE OF REINFORCEMENT ON DEFLECTIONS DUE TO 15-KIP WHEEL LOADS

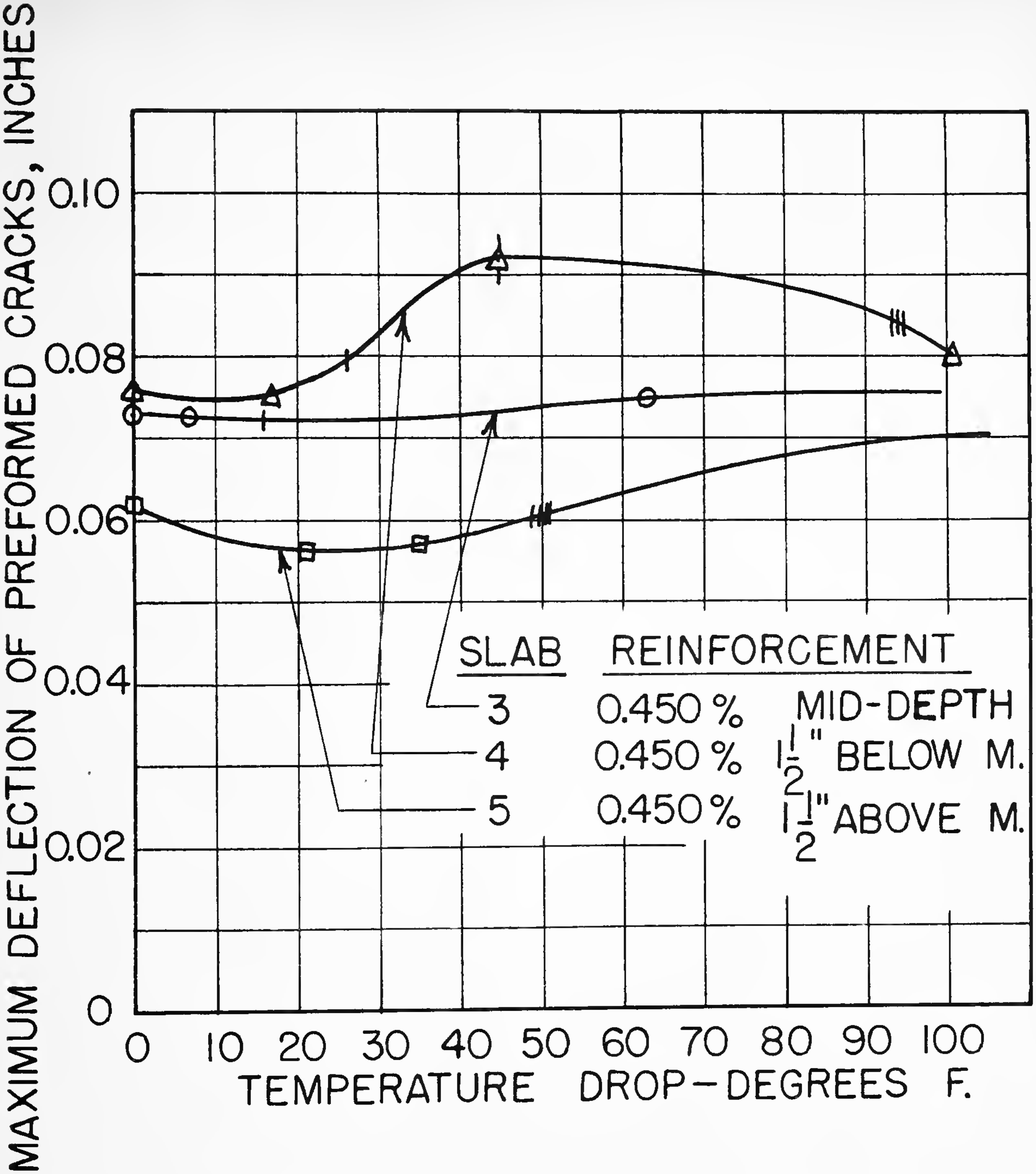


FIG. 5 - INFLUENCE OF TEMPERATURE DROP AND POSITION OF REINFORCEMENT ON DEFLECTIONS DUE TO 15-KIP WHEEL LOADS

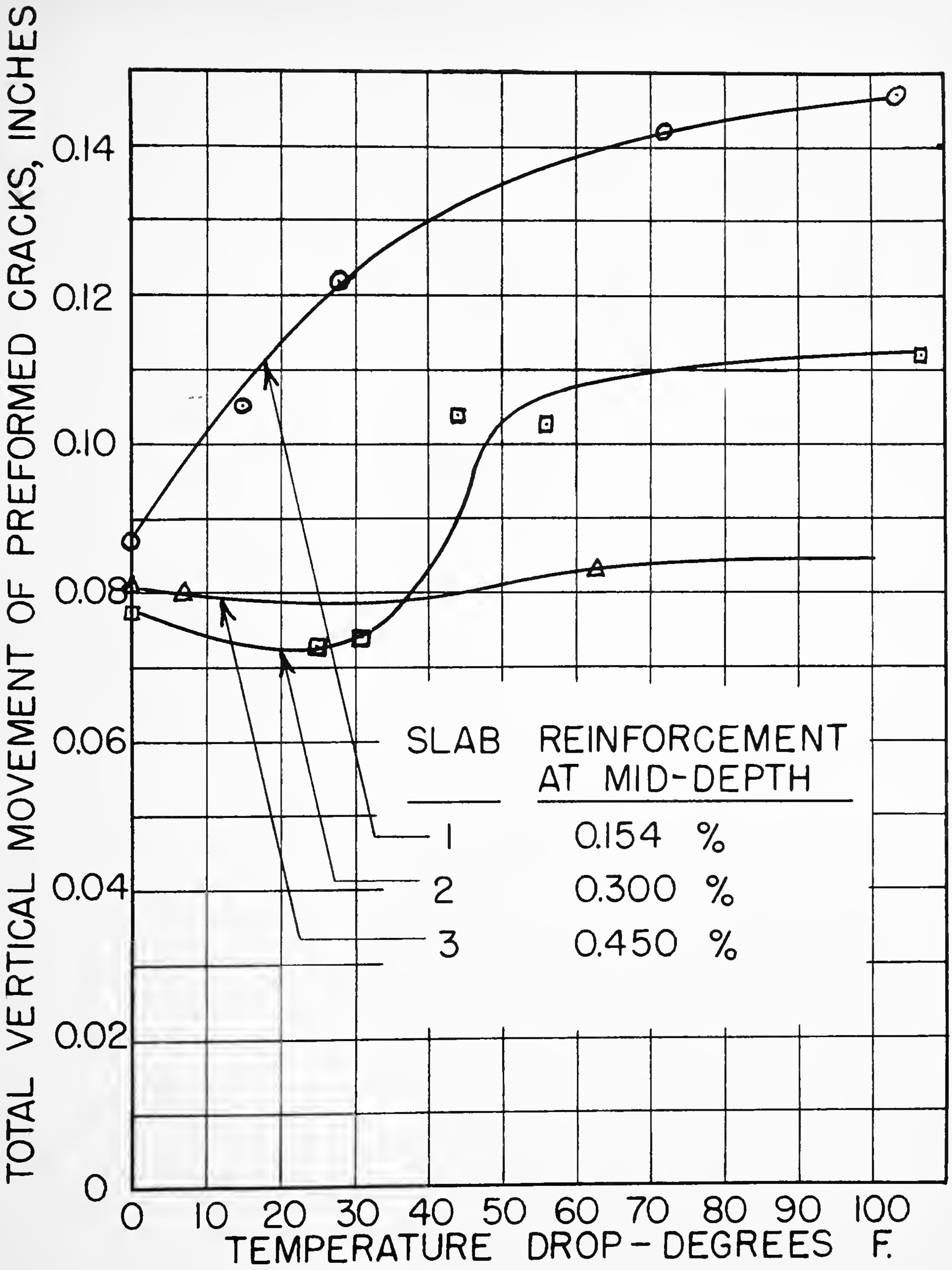


FIG. 6 - INFLUENCE OF TEMPERATURE DROP AND PERCENTAGE OF REINFORCEMENT ON TOTAL VERTICAL MOVEMENT DUE TO 15-KIP WHEEL LOADS

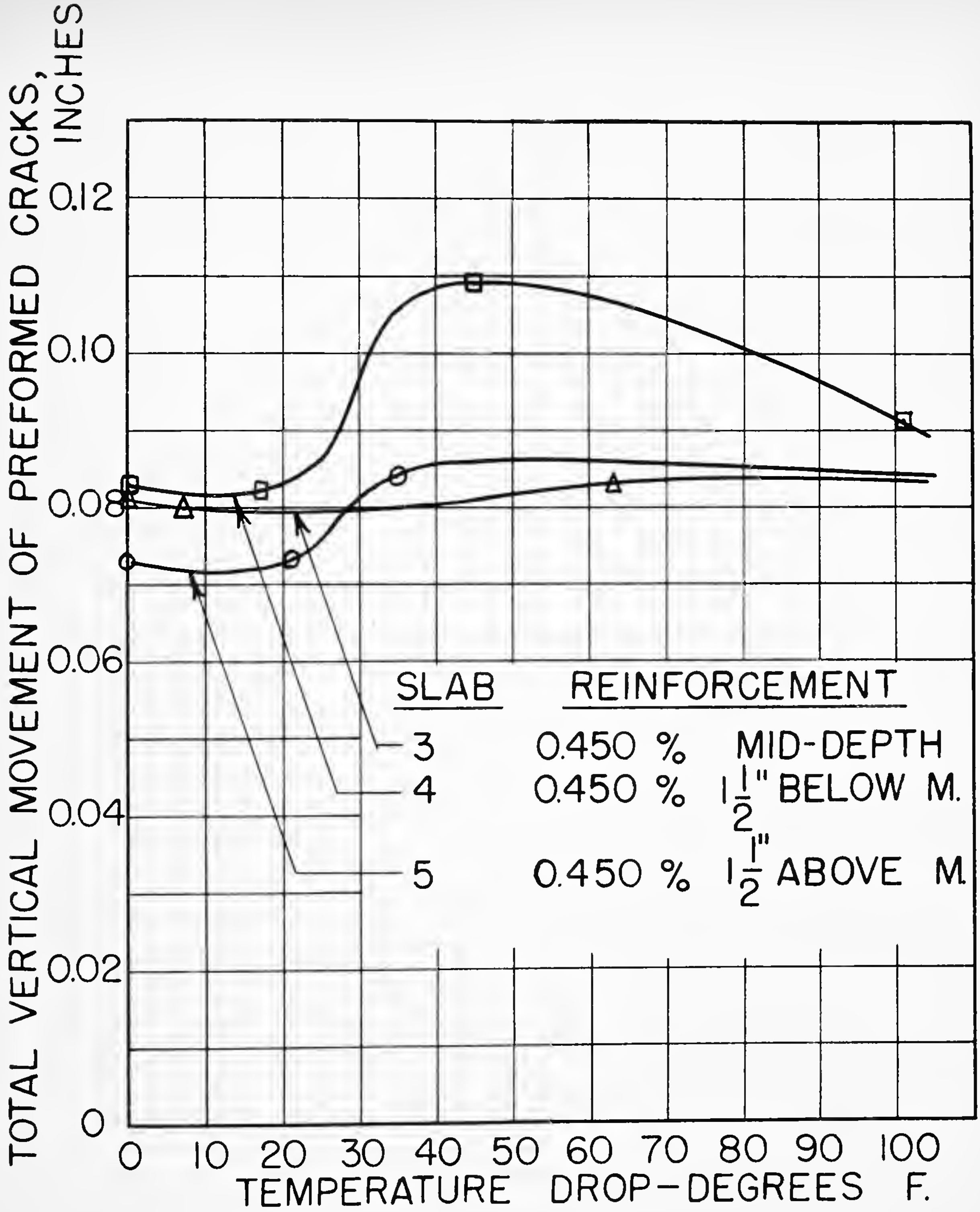


FIG. 7- INFLUENCE OF TEMPERATURE DROP AND POSITION OF REINFORCEMENT ON TOTAL VERTICAL MOVEMENT DUE TO 15-KIP WHEEL LOADS

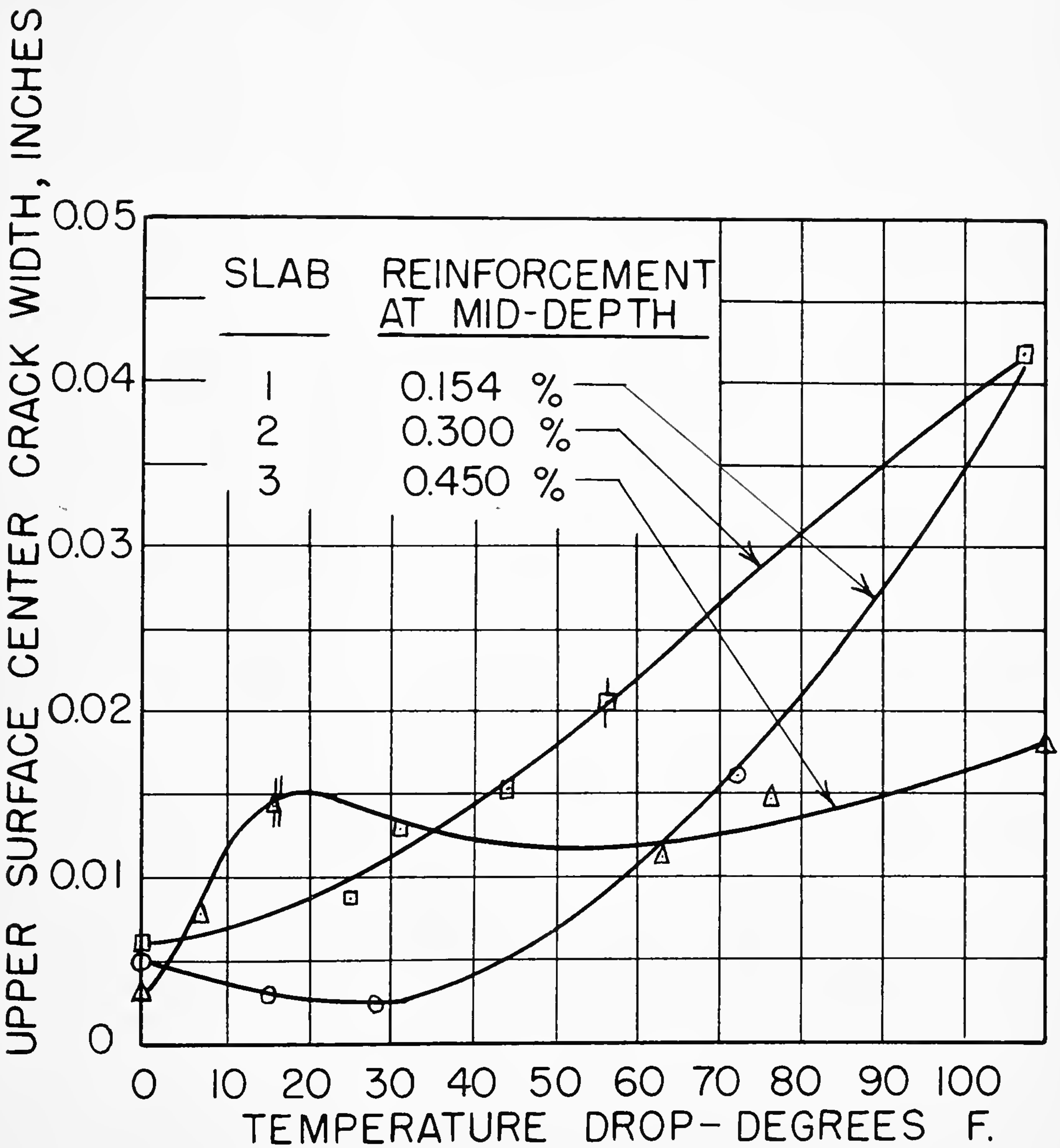


FIG. 8 - INFLUENCE OF TEMPERATURE DROP AND PERCENTAGE OF REINFORCEMENT ON UPPER SURFACE CRACK WIDTHS

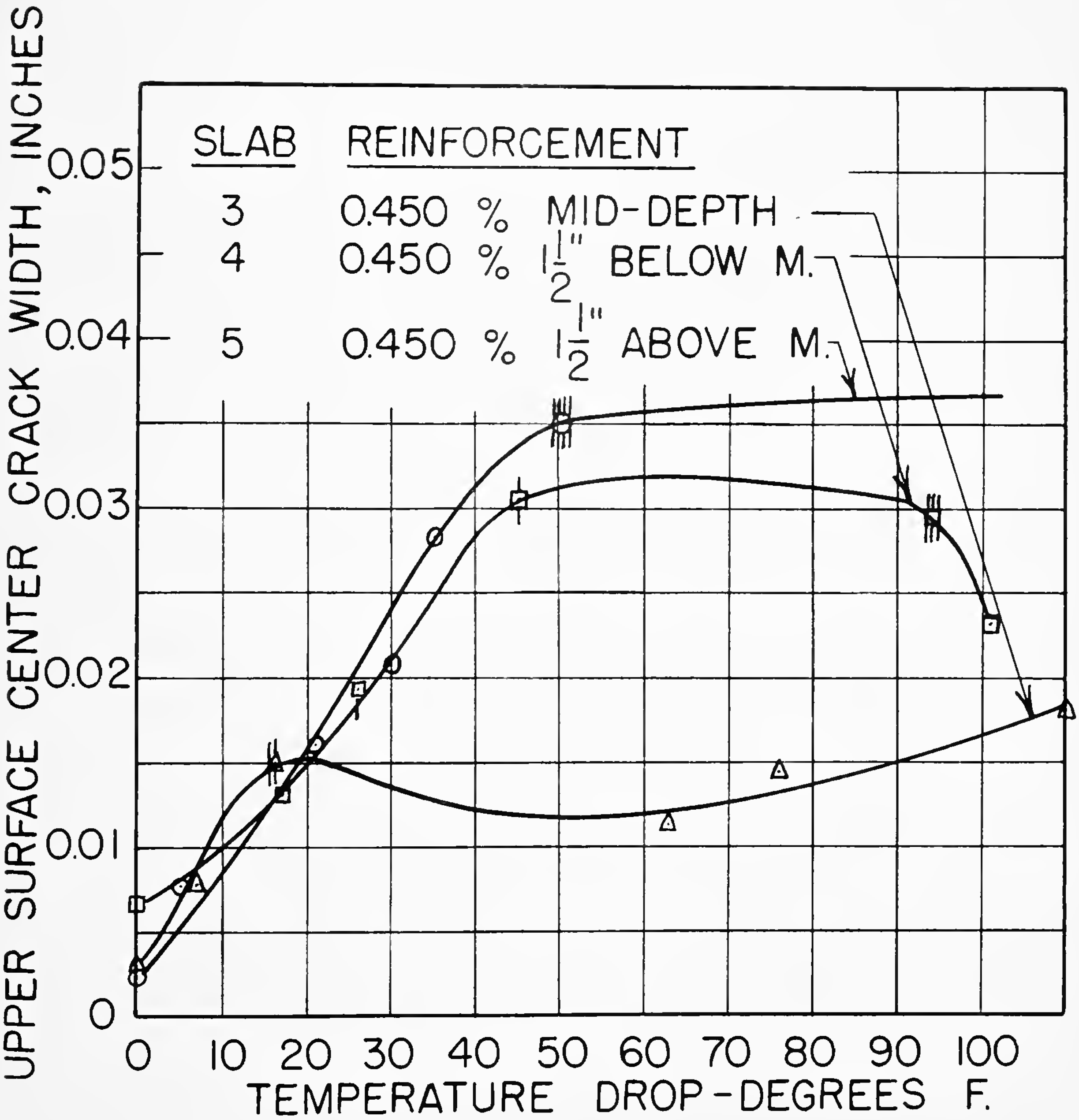
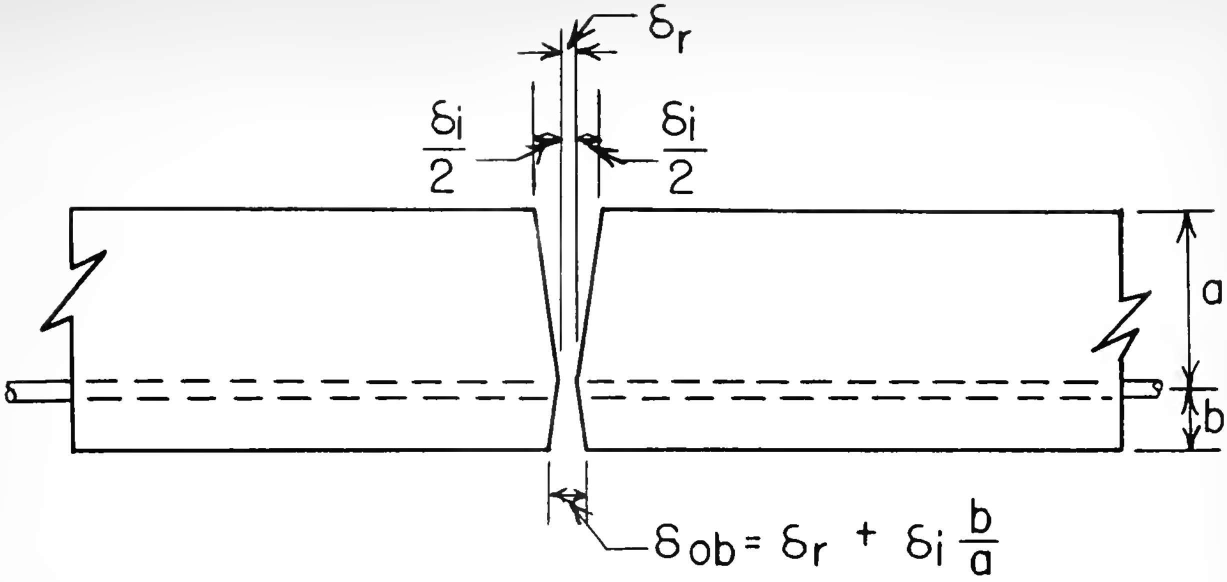
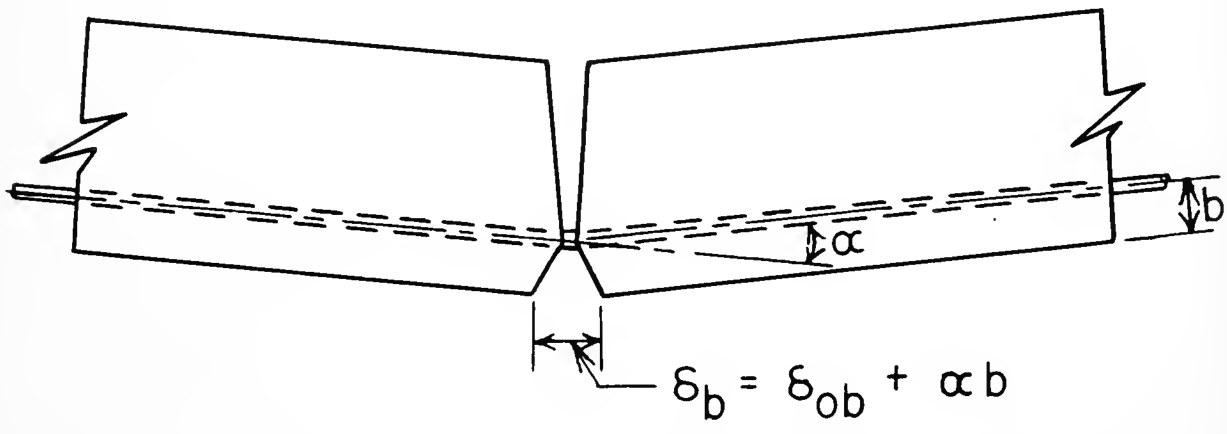


FIG. 9- INFLUENCE OF TEMPERATURE DROP AND POSITION OF REINFORCEMENT ON UPPER SURFACE CRACK WIDTHS



(a) CRACK DUE TO TEMPERATURE DROP



(b) CRACK DUE TO TEMPERATURE DROP AND VERTICAL LOAD

FIG. 10 - DEFORMATIONS AT A CRACK

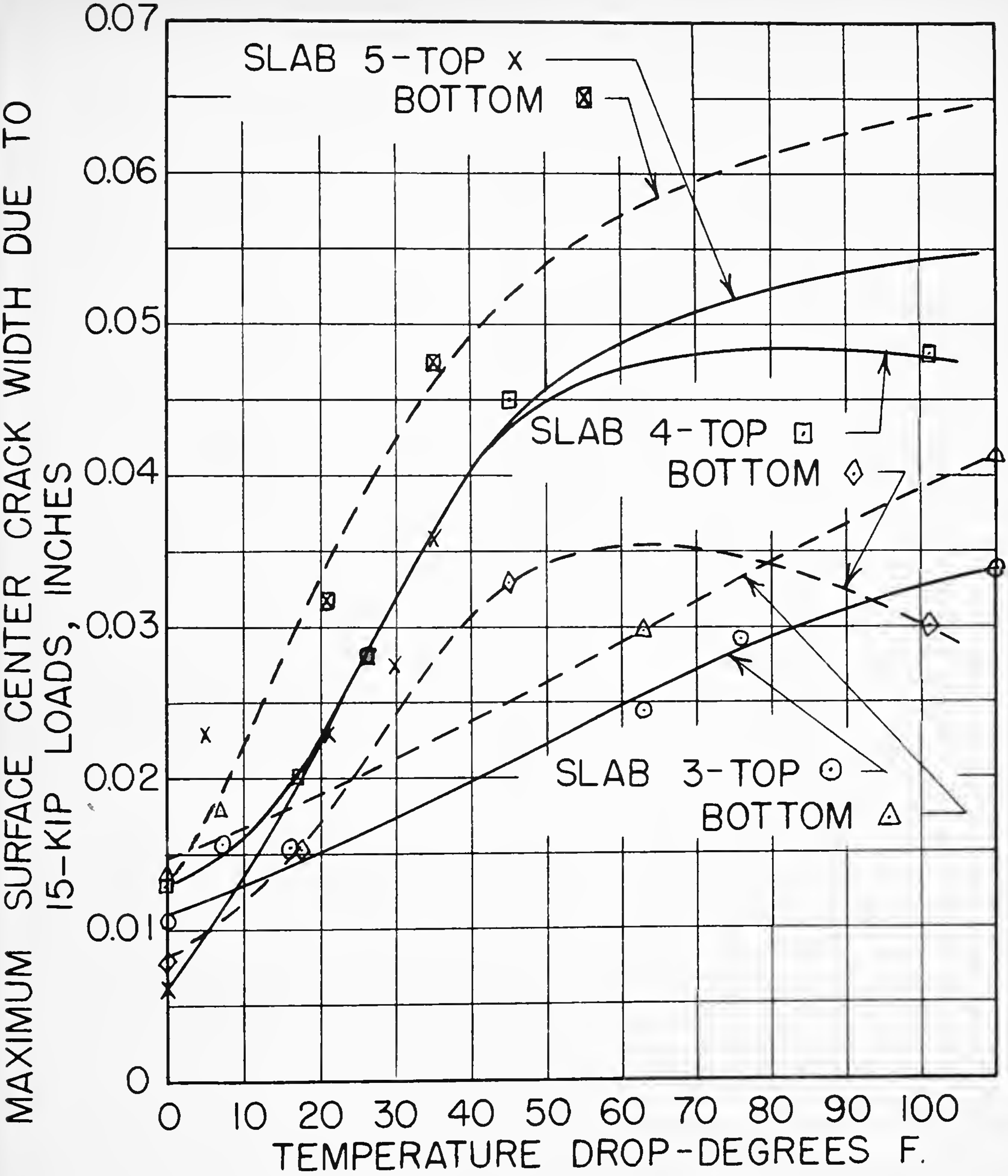


FIG. 11- INFLUENCE OF TEMPERATURE DROP AND POSITION OF REINFORCEMENT ON MAXIMUM SURFACE CRACK WIDTHS DUE TO 15-KIP WHEEL LOADS

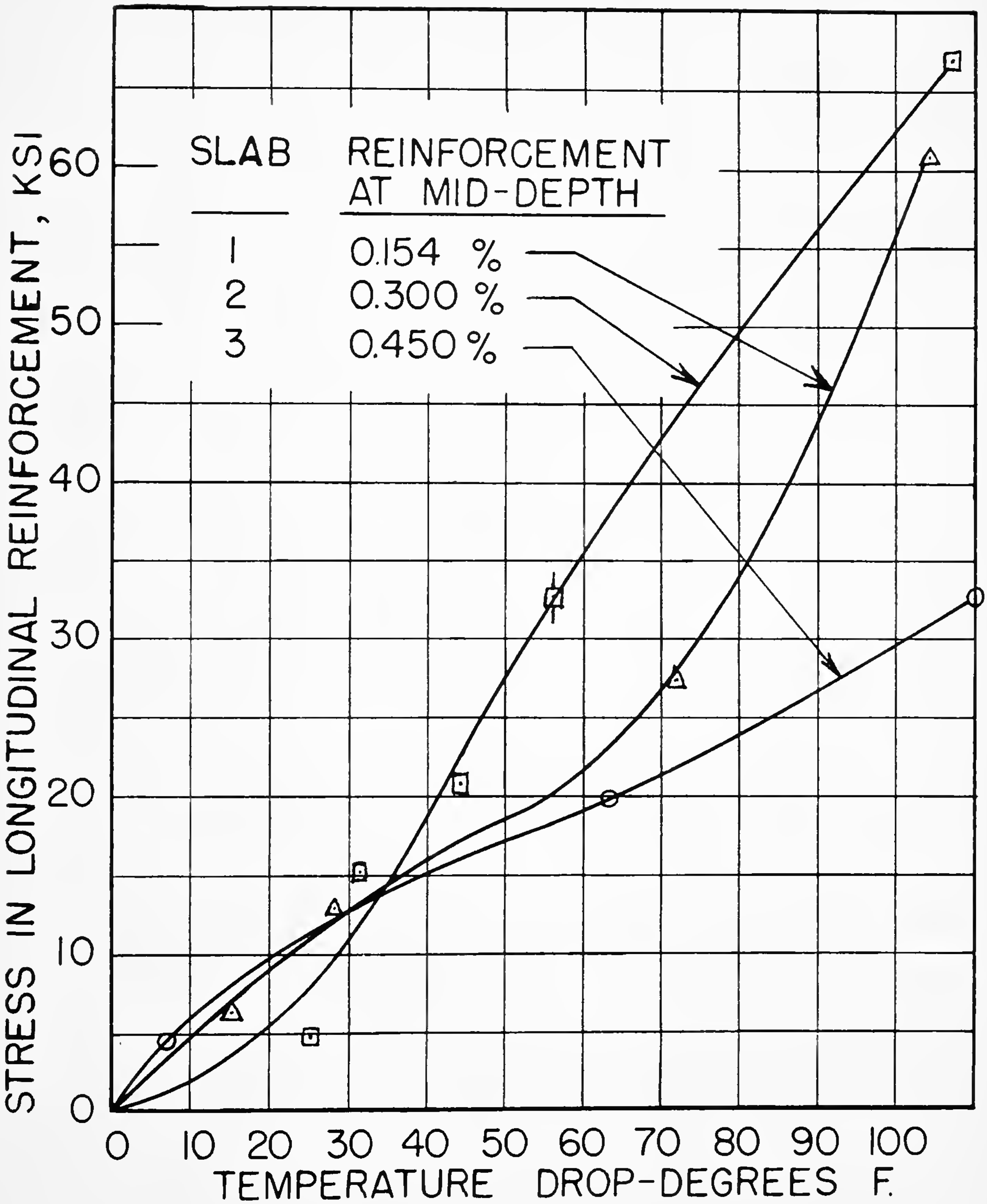


FIG. 12 - INFLUENCE OF TEMPERATURE DROP AND PERCENTAGE OF REINFORCEMENT ON STRESS IN STEEL AT CENTER CRACK

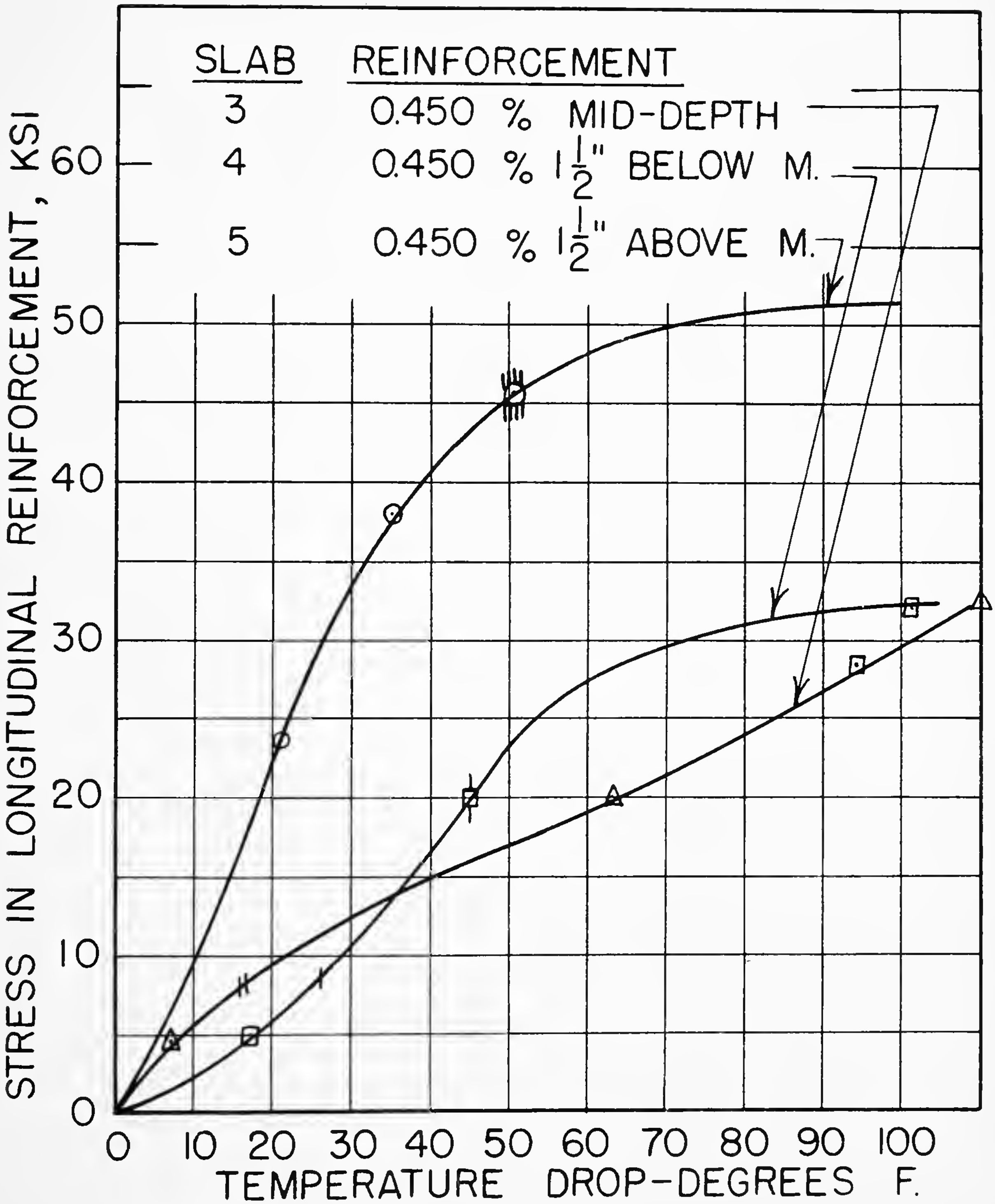


FIG. 13 - INFLUENCE OF TEMPERATURE DROP AND POSITION OF REINFORCEMENT ON STRESS IN STEEL AT CENTER CRACK

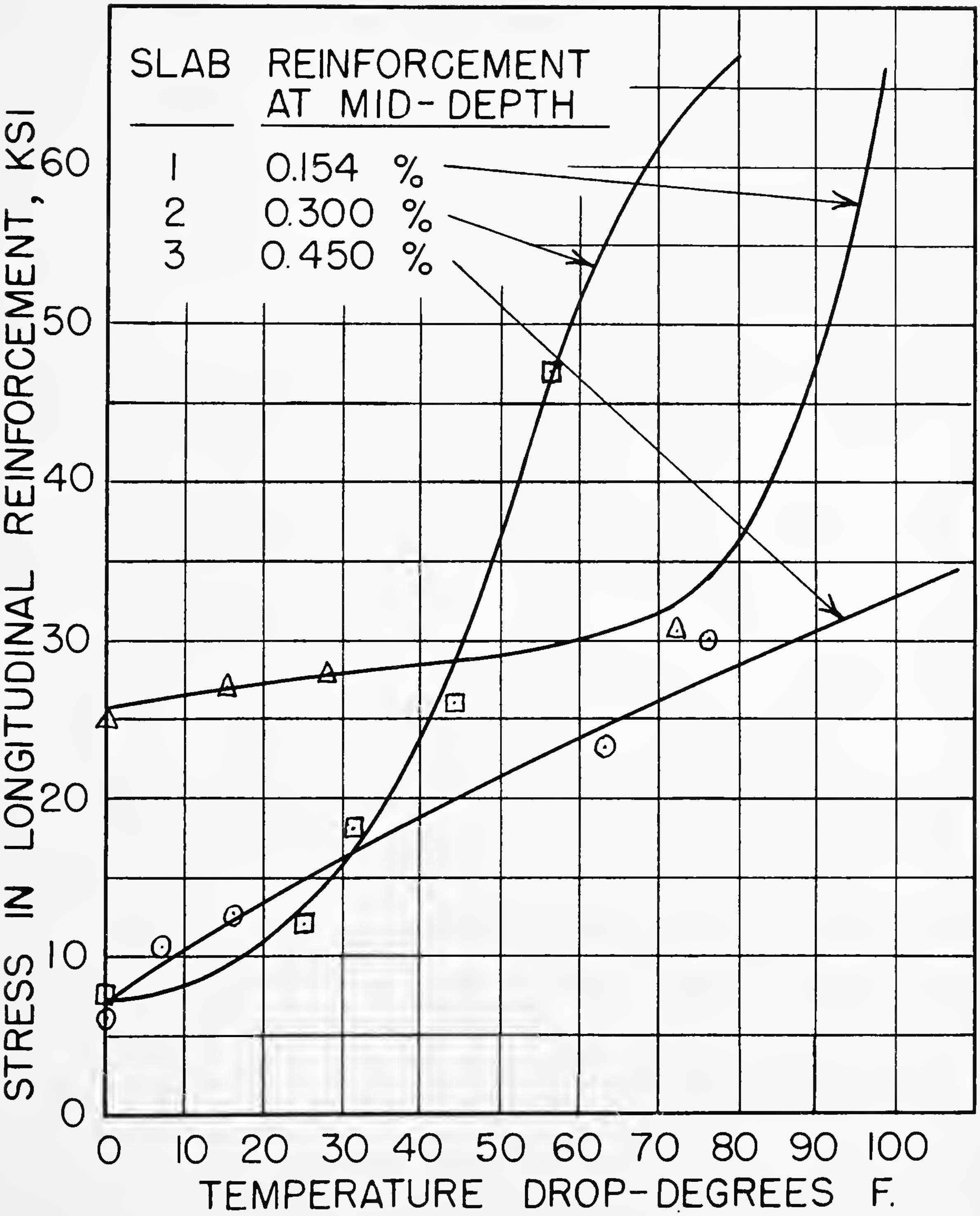


FIG. 14-INFLUENCE OF TEMPERATURE DROP AND PERCENTAGE OF REINFORCEMENT ON STRESS IN STEEL AT CENTER CRACK DUE TO 15-KIP WHEEL LOADS

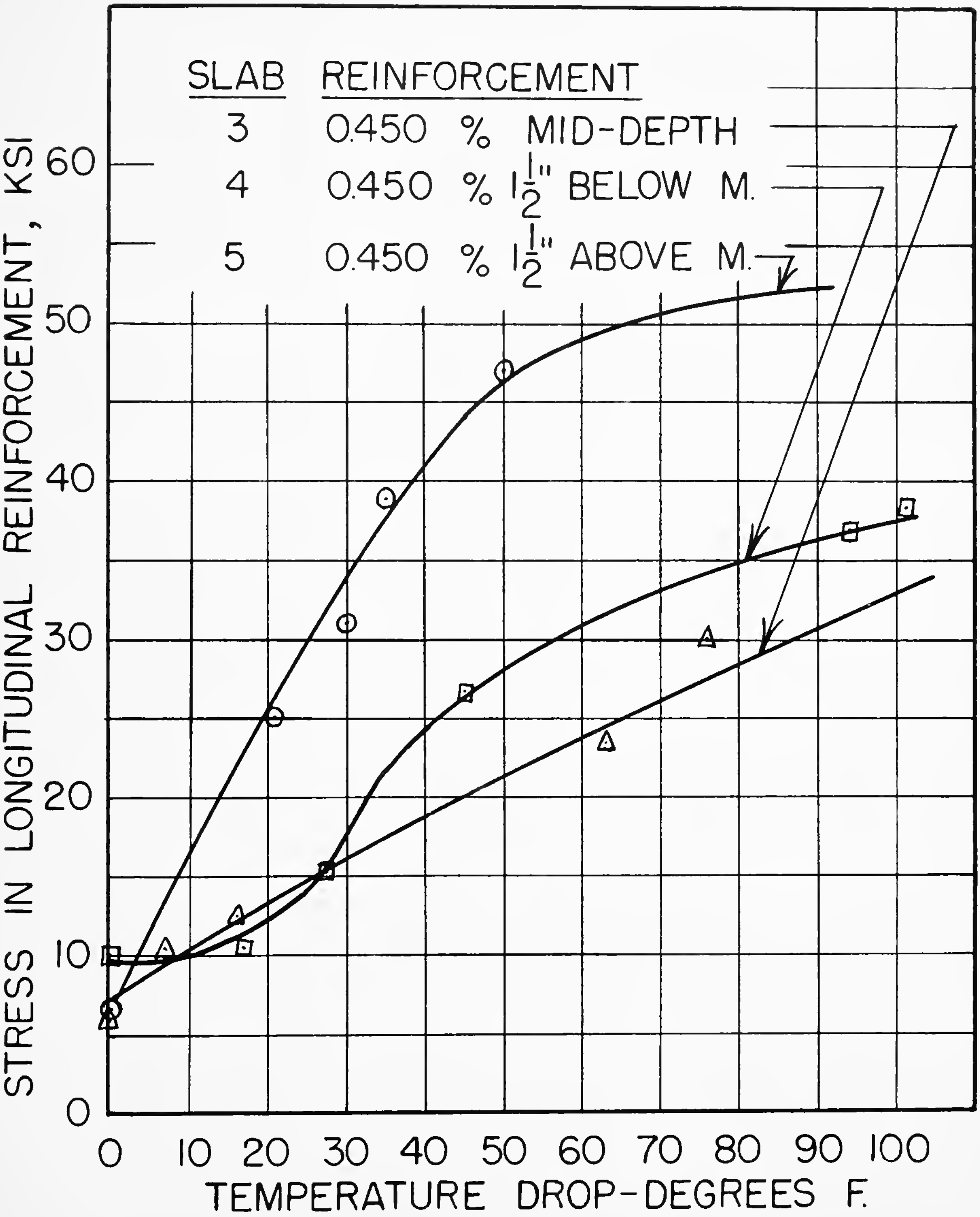


FIG. 15 - INFLUENCE OF TEMPERATURE DROP AND POSITION OF REINFORCEMENT ON STRESS IN STEEL AT CENTER CRACK DUE TO 15-KIP WHEEL LOADS